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THE ISENTROPE OF UNREACTED LX-04 TO 170 kbar

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Abstract. We present new data on the unreacted approximate isentrope of the HMX-based explosive LX-04, measured to 170 kbar, using newly developed long pulse isentropic compression techniques at the Sandia National Laboratories Z Machine facility. This study extends in pressure by 70% the previous state of the art on unreacted LX-04 using this technique. This isentrope will give the unreacted Hugoniot from thermodynamic relations using a Gruneisen equation of state model. The unreacted Hugoniot of LX-04 is important in understanding the structure of the reaction front in the detonating explosive. We find that a Hugoniot given by U_S = 2950 m/s + 1.69 u_P yields for an isentrope a curve which fits our LX-04 ICE data well.

INTRODUCTION

LX-04 is an important weapons-related secondary high explosive formulation composed of 85% HMX (octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine) and 15% Viton-A (vinylidene fluoride/hexafluoropropylene copolymer) [1]. The unreacted Hugoniot of LX-04 is important for a detailed understanding of the impulse it will deliver during detonation. It is difficult to measure the properties of unreacted explosives by conventional shock compression techniques, which tend to initiate detonation. On the other hand, ramp wave compression, such as is achieved in Isentropic Compression Experiments (ICE), is believed to be inherently a lower temperature dynamic loading process than shock compression. The ICE technique has already been demonstrated to be very effective at dynamically loading high explosives without reaction, and experiments have already been performed on LX-04 as well as various other explosives [2,3]. The previous ICE work on LX-04 extended to 100 kbar [2], but recent improvements in waveform shaping motivated us to attempt to remeasure the LX-04 isentrope to higher pressures.

Our ICE experiments were conducted at Sandia National Laboratories Z Machine facility. The ICE technique [4,5] generates a large-amplitude (hundreds of kbar) compression wave of a few hundreds of nanosecond rise time (by comparison, shock wave rise times can be sub-nanosecond). This ramp wave is launched into the sample by magnetic pressure developed by an enormous current density in a conductive "floor" upon which the sample is mounted (For all our samples this floor was 800 μm of 6061-aluminum.). This current creates a time-dependent pressure boundary condition on the interior floor interface (the a-b interface of Fig. 2). References 4 and 5 contain excellent descriptions of this versatile technique.

PROCEDURE

Full density LX-04 samples of six different thicknesses and two NaCl (100) samples were mounted on four panels made from 6061 aluminum. Each panel is precision machined to 800 μm thick in three places. Thus each panel will accommodate three samples. All samples used a NaCl (100) VISAR window. In addition, four LiF (100) windows were mounted, one per panel, directly on the Al floor to monitor the drive uniformity between panels. NaCl is a better acoustic impedance match to HE than the more popular LiF but it has a phase transition at about 260 kbar [6]. However, this limitation does not impact our data as 260 kbar is still beyond the pressure range of this work. Commercially available VALYN VISAR equipment was used. The refractive index-density relations of Wackerle and Stacy [6] were used for the NaCl windows. Figure 1 shows the four panels with mounted samples. Current flow is in the same direction as the line of samples. Figure 2 is a diagram illustrating an individual sample assembly.

FIGURE 1. The four panels with samples and windows mounted (twelve sample locations total). To give an idea of size, the windows are 6.00 mm diameter.

RESULTS/DISCUSSION

The ICE load curve in P-V space was computed based on the work of Fowles and Williams [7]:

$$c_L(u) = \frac{x_{01} - x_{02}}{t_1(u) - t_2(u)} \qquad \text{(Eq. 1)}$$

$$dP = \rho_0 c_L(u)\, du \qquad \text{(Eq. 2)}$$

$$\left(\frac{\partial P}{\partial \rho}\right)_S = c_E^2 = \frac{\rho_0^2}{\rho^2}\left(c_L(P)\right)^2 \qquad \text{(Eq. 3)}$$

In these equations: c_L is the Lagrange sound speed. u is the sample particle velocity. x_{01} is the inital thickness of sample 1, t_1 is the arrival time of the wave of amplitude u at the VISAR interface of sample 1. ρ_0 and ρ are initial density and density respectively, and c_E is the Eulerian sound speed. Equation 1 is nothing

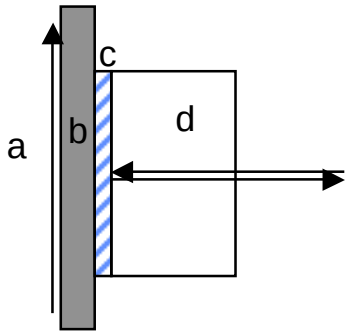

FIGURE 2. Side cut-away view of sample assembly. a) The assembly interior. It can be thought of as the interior of a short-circuited waveguide where a large magnetic field is developed by the current. b) the aluminum floor. The large surface current (vertical arrow) flows at the boundary between "a" and "b". The return conductor (known as the "stem") is to the left of "a" and is not shown. The floor serves both as a conductor for the current and to drive the ramp wave in the sample. c) the sample. d) the window. The interface between "c" and "d" is coated with 250 nm of silver to efficiently reflect the VISAR probe light, represented by the horizontal arrows.

more than a recipe for calculating c_L from VISAR data. Equation 2 allows us to eliminate the variable u in favor of the more useful P. Equation 3 is then integrated to get the isentrope. We do not consider material strength and do not distinguish between longitudinal wave stress and pressure P. A minimal data set for an analysis is two VISAR velocity histories from samples of the same material but of different initial thicknesses. Such an "EOS (equation of state) pair" of histories is represented by Fig. 3, for example. All LX-04 histories showed no clear evidence of reaction and looked quite similar to the histories of the (nonreactive) NaCl.

Equations 1-3 are appropriate to plane isentropic simple wave loading, and finite reflection from the sample-window interface spoils the simple wave assumption. Our window material NaCl is well (but not perfectly) matched to LX-04. We corrected u using NaCl and LX-04 Lagrange sound speeds measured in this experiment. Hayes [8] elaborates on the zero-order nature of this type of correction, which according to his Fig. 1 leads to a 10% error in the worst case scenario (i.e. free surface). However, given that our zero-order correction increased u by less than 10% over its full range, we estimate 1-2% error in neglecting the higher order corrections for our specific case.

Unfortunately all our LX-04 waveforms shocked up slightly at the base. We treated the shock as setting up an initial state to a pressure given by the average strength shown in the two waveforms used to create a data set. This average initial shocked state is the starting point for the integration of Eqs. 2 and 3. The results of such a computation performed on our data are displayed in Fig. 4. Also shown in Fig. 4 is a linear (in U_S, u_P) Hugoniot (dashed line) and the associated isentrope (solid line) derived from this Hugoniot using a Gruneisen gamma model with the constant gamma/volume assumption. We used a Γ_0 of 1.25 based on thermodynamic data [1]. Based on the good agreement between the derived isentrope and our data we conclude that the Hugoniot given by U_S = 2950 m/s + 1.69 u_P represents the unreacted Hugoniot data for full density LX-04 between 0 and 170 kbar. Our data are in good agreement with the previous ICE work on LX-04 [2] within their range of mutual overlap (up to 100 kbar). However our extended data range shows a less stiff response beyond 100 kbar than the extrapolated Hugoniot derived from the previous work would suggest. Hydrodynamic simulations using the Trac II code further support this conclusion.

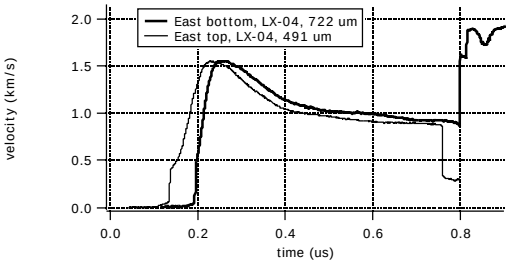

FIGURE 3. An EOS pair of LX-04 samples. The lack of amplitude growth at the peak and in the following rarefaction is evidence for insignificant reaction.

Figure 5 shows a comparison of the room temperature isotherm of pure HMX [9] to our LX-04 results. The isotherm appears to be slightly stiffer than our Hugoniot. We claim that the difference is due to the 15 % binder composition of LX-04. We do not know of any EOS data for Viton-A in the literature but we did plot the Hugoniot for the somewhat similar Teflon [10]. Clearly the incorporation of 15 % of a soft Teflon-like material will soften the mixture's P-V curve relative to pure HMX.

SUMMARY AND FUTURE WORK

We used the ICE technique and the improved pulse shaping capabilities of the Z machine at SNL to measure the unreacted

approximate isentrope of full density LX-04 to 170 kbar, 70 % higher than previous work. From our data we compute an unreacted Hugoniot for LX-04 given by U_S = 2950 m/s + (1.69) u_p. This data is reasonably consistent with existing HMX isotherm data.

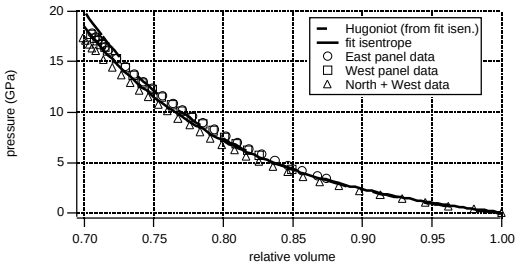

FIGURE 4. Results of this work: LX-04 isentrope data, fitted isentrope, and Hugoniot derived from this fitted isentrope. The derived Hugoniot parameters are A = 2950 m/s, B = 1.69. Note pressure units are GPa on the graphs. Our estimate of uncertainty is +/- 5% in *P* at a given relative volume.

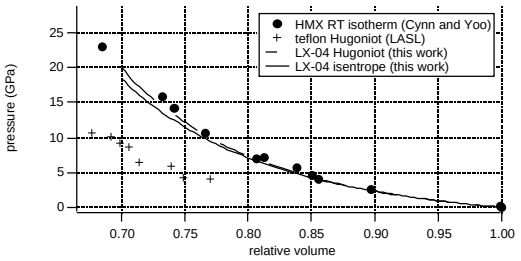

FIGURE 5. Comparison of HMX room temperature isotherm (Ref. 9), Teflon Hugoniot (Ref. 10), and the fitted LX-04 isentrope and its derived Hugoniot (this work).

We are hopeful that future advances will allow us to extend the pressure range on this and other HEs. We hope to have some Viton-A EOS data available in the near future so that detailed comparisons can be made between pure HMX data and LX-04 data.

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